Chapter

Nanosatellites and Applications to Commercial and Scientific Missions

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Abstract

In the past two decades, a silent revolution has taken place in the space domain, leading to what today is known as "New Space." We have passed from a selected group of countries, space agencies, and big industries building, launching, and operating satellites and other spacecrafts, of a scenario in which many universities and research institutes can do it. The key of this was the definition of the "CubeSat" standard, back to 1999. In 2013, it all took off on the commercial Earth Observation sector with the first launches from two companies that are now running 100+ CubeSat constellations for optical imaging or weather prediction, with very low revisit times. Today, the same revolution is taking place in the fields of Telecommunications, and Astronomical Scientific missions. In this chapter, the evolution of the space sector is briefly revised until the arrival of the CubeSats. Then, the CubeSat intrinsic limitations are discussed as they are key to understand the development and current situation of the CubeSat sector. NASA and ESA strategies are also presented. The chapter concludes with a summary of the technology roadmap to enable the next generation of CubeSat-based missions, including satellite constellations or federations, formation flying, synthetic apertures...

Keywords: satellites, CubeSats, mission, earth observation, astronomy, planetary exploration, enabling technologies

1. Introduction

1.1 From the sputnik to the CubeSats

At the beginning of the space age, all satellites were "small." Sputnik 1 was the first artificial Earth satellite (**Figure 1a**) [1]. It was launched by the Soviet Union from Baikonur Cosmodrome on October 4, 1957, into an elliptical low Earth orbit (LEO) with an inclination of 65°. Sputnik 1 was a 58-cm-diameter metal sphere, weighing approximately 84 kg, with four radio antennas transmitting at 20.005 and 40.002 MHz. Tracking and studying Sputnik 1 signals from Earth provided valuable information on upper atmosphere density, and the propagation of radio signals provided information on the ionosphere. Sputnik did not have solar panels, so the mission ended after 3 weeks when batteries died.

Explorer 1 was the first US satellite (**Figure 1b**) [2], and the third one after Sputnik 1 and 2. It was launched from Cape Canaveral, Florida, on January 31, 1958. Explorer 1 was 205 cm tall and 15 cm in diameter, weighing nearly 14 kg. It was the first spacecraft to detect the Van Allen radiation belts. Explorer 1 did not have solar panels either, so after 4 months the mission ended when batteries were exhausted.

Vanguard 1 was the fourth artificial Earth satellite (**Figure 1c**) [3]. It was launched by the USA from Cape Canaveral on March 17, 1958, into a 654 by 3969 km elliptical orbit with an inclination of 34.25°. Vanguard 1 was a 16.5-cm-diameter aluminum sphere, weighing just 1.47 kg, and it was the first satellite with six solar cells powering two beacons at 108 and 108.03 MHz, which were used to measure the total electron content.

During the first two decades of the space age, each satellite had its own design. They were the art pieces of the space craftsmen. Standard spacecraft busses were practically unknown until the end of the 1970s. In the early 1980s, microsatellites emerged and adopted a radically different design approach to reduce costs, focusing on available and existing technologies and using properly qualified commercial off-the-shelf (COTS) components.

For many years, satellite mass increased as illustrated in **Table 1**. However, except for some military, astronomy, and specific communication applications, it seems that the era of massive satellites is over.

The "small satellite mission philosophy" represents a design-to-cost approach, with strict cost and schedule constraints, often combined with a single mission objective in order to reduce complexity. **Figure 2** from [14] summarizes the standardized definition of satellites according to their weight: picosatellites (0.1–1 kg), nanosatellites (1–10 kg), microsatellites (10–100 kg), and mini-satellites or small/medium satellites (100–1000 kg).

In the field of Earth observation (EO), this has led to smaller target-focused missions which, with reduced spacecraft and launch costs (shared rides), are enabling massive (>100) satellite constellations of nano- and microsatellites with reduced revisit times, unthinkable just a few years ago.

In the field of satellite communications, there are plans as well to deploy massive constellations of LEO satellites to provide worldwide Internet coverage, IoT services, and machine-to-machine (M2M) communications.

It is anticipated that enhanced inter-satellite communication capabilities (LEO-ground, LEO-LEO, LEO-MEO, and LEO-GEO) will also improve the performance of EO systems [15]. All this is leading to the evolution of the space segment from monolithic to distributed and federated satellite systems [16], aiming at establishing win-win collaborations between satellites to improve their mission performance by using the unused onboard resources.

a) b) c)

Figure 1.
Pictures of (a) sputnik 1 [4], (b) explorer 1 [5], and (c) vanguard 1 [6].

Spacecraft	Agency application	Mass	Duration
KH-11 Kennen (a.k.a. CRYSTAL, EECS, 1010) [7]	US NRO/optical imaging	19,600 kg	1976–present
Proton [8]	USSR/astronomy	17,000 kg	1965–1969
Compton Gamma Ray Obs. [9]	US NASA/astronomy	16,329 kg	1991–2000
Lacrosse [10]	US NRO/SAR	14,500–16,000 kg	1988–2005
Hubble Space Telescope [11]	US NASA/astronomy	11,110 kg	1990–present
ENVISAT [12]	ESA/Earth observation	8211 kg	2002–2012
Telstar 19 V [13]	Canada/communications	7075 kg	2018–present

Table 1.
Heaviest spacecrafts (excluding space stations and manned orbiters).

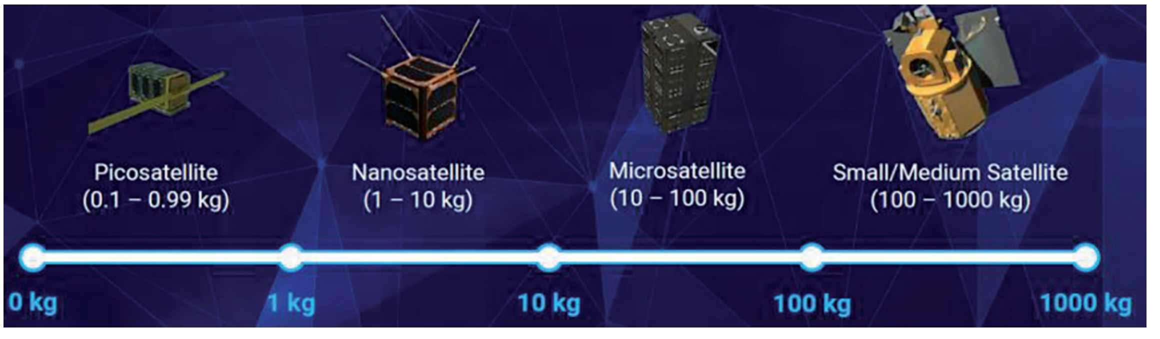


Figure 2.
Satellite classification [14].

1.2 The CubeSat standard

The so-called CubeSat standard was conceived in 1999 by Profs. Jordi Puig-Suari of California Polytechnic State University (CalPoly) and Bob Twiggs of Stanford University to allow graduate students to conceive, design, implement, test, and operate in space a complete spacecraft in a "reasonable" amount of time (i.e., the duration of their studies). CubeSats are small satellite multiples of 1 U (1 U: 10 cm × 10 cm × 11.35 cm, weighing less than 1.33 kg), including all the basic subsystems as large satellites but using COTS components. The CubeSat "standard" only defines the mechanical external interfaces, i.e., those referring to the orbital deployer. Originally, it was never meant to be a standard, however, because of its simplicity, it soon became a "de facto" standard. As Prof. Twiggs said in an interview to Spaceflight Now in 2014: "*It all started as a university education program satellite. It was kind of funny. I didn't think that people would criticize it as much as they did, but we got a lot of feedback (…). Another thing that was kind of funny we had no interest from NASA or any of the military organizations. It just wasn't anything they were interested in, so it was all funded without any funding from those aerospace organizations*." The first six CubeSats were launched on a Russian Eurockot on June 30th, 2003. Then, after more than a decade in which the concept silently matured in university labs, space agencies got interested and showed that CubeSat-based mission reliability could be improved by proper engineering. In 2013, it all took off on the commercial Earth Observation sector with the first launches from two companies that are now running 100+ CubeSats constellations for optical imaging or weather prediction, with very low revisit times. Today, many of the initial CubeSat limitations (most notably size, available power, and down-link bandwidth) are being overcome, and the same revolution is starting to take place in the fields of telecommunications, and astronomical scientific missions.

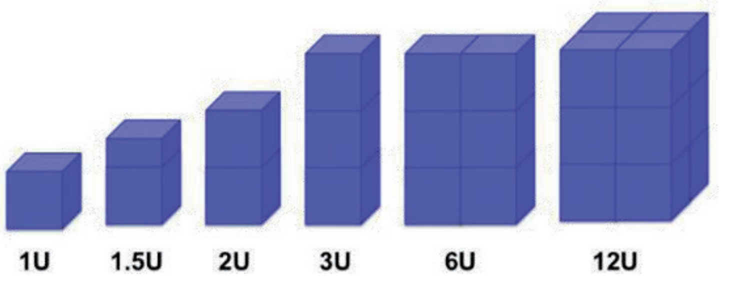


Figure 3.
CubeSat form factors from 1 U to 12 U [20].

The current CubeSat Design Specification defines the envelopes for 1 U, 1.5 U, 2 U, 3 U and 3 U+, and 6 U form factors (see, e.g., CubeSat Design Specification Rev. 13 or 6 U CubeSat Design Specification in [17], **Figure 3**), and the standardization of 12 U and 16 U is in progress, although some companies have produced standards up to 27 U [18]. On the other side, smaller picosatellites, the so-called PocketQubes, about 1/8 the size of a CubeSat, have also been standardized [19].

Probably, what has had the most significant impact in the popularization of the CubeSat standard has been the capability to separate the interface between the spacecraft and the poly-picosatellite orbital deployer (P-POD) and between the dispenser and the rocket itself. There are two different classes of PODs. The first type is the classical one with four rails in the corners [17], and the second one is with tables [18]. Note however that modern deployers from ISIS and NanoRacks allow larger deployables, wider solar panels, and thinner rails as compared to original P-POD, e.g., increased extruded height up to 9 mm and up to 2 kg per 1 U.

As of June 2019, 64 countries have launched nanosatellites or CubeSats. The total number of nanosatellites launched is 1186, from which 1088 are CubeSats. Most of them (273) have been launched from the International Space Station at ~400 km orbital height with an inclination of 51.6° and the rest at low Earth orbits (LEO) typically at 500 km sun-synchronous orbit (SSO) with an inclination of 97.5° (217 CubeSats) and 580 km height with 97.8° inclination (80 CubeSats). So far, only two (MarCO-1 and MarCO-2) have performed interplanetary missions.

1.3 Current status

Figure 4 shows the number of nanosatellites launched per year (a) and organization, either companies, universities, space agencies, etc., or (b) form factor from picosats, 0.25 up to 16 U.

As it can be appreciated, until 2013 most CubeSats were launched by universities and research institutes, and most of them were 1 U or 2 U. However, in 2013 the first 3 U CubeSats from the Planet Labs Inc. [22] and Spire Global Inc. [23] were launched. That was the beginning of today's revolution in EO, and—as of June 10, 2019—these two companies had launched the largest commercial constellations ever with 355 and 103 CubeSats, respectively. The following ones have launched at most seven CubeSats. Therefore, 3 U CubeSats are dominating the scene, and they will over the next decade, followed by far by the 1 U, 2 U, and 6 U form factors (**Figure 5**). However, it is expected that the next wave of growth will be based on 6 U and 12 U CubeSats, which offer the right balance between very capable payloads and limited manufacturing and launch costs.

Table 2 (extracted from the database in [21]) shows the main companies that have launched CubeSats, the number of launched and planned CubeSats, the year of the first launch, the form factor, the application field, and some technical details. The rows marked in light blue correspond to EO optical imaging, in light green to EO

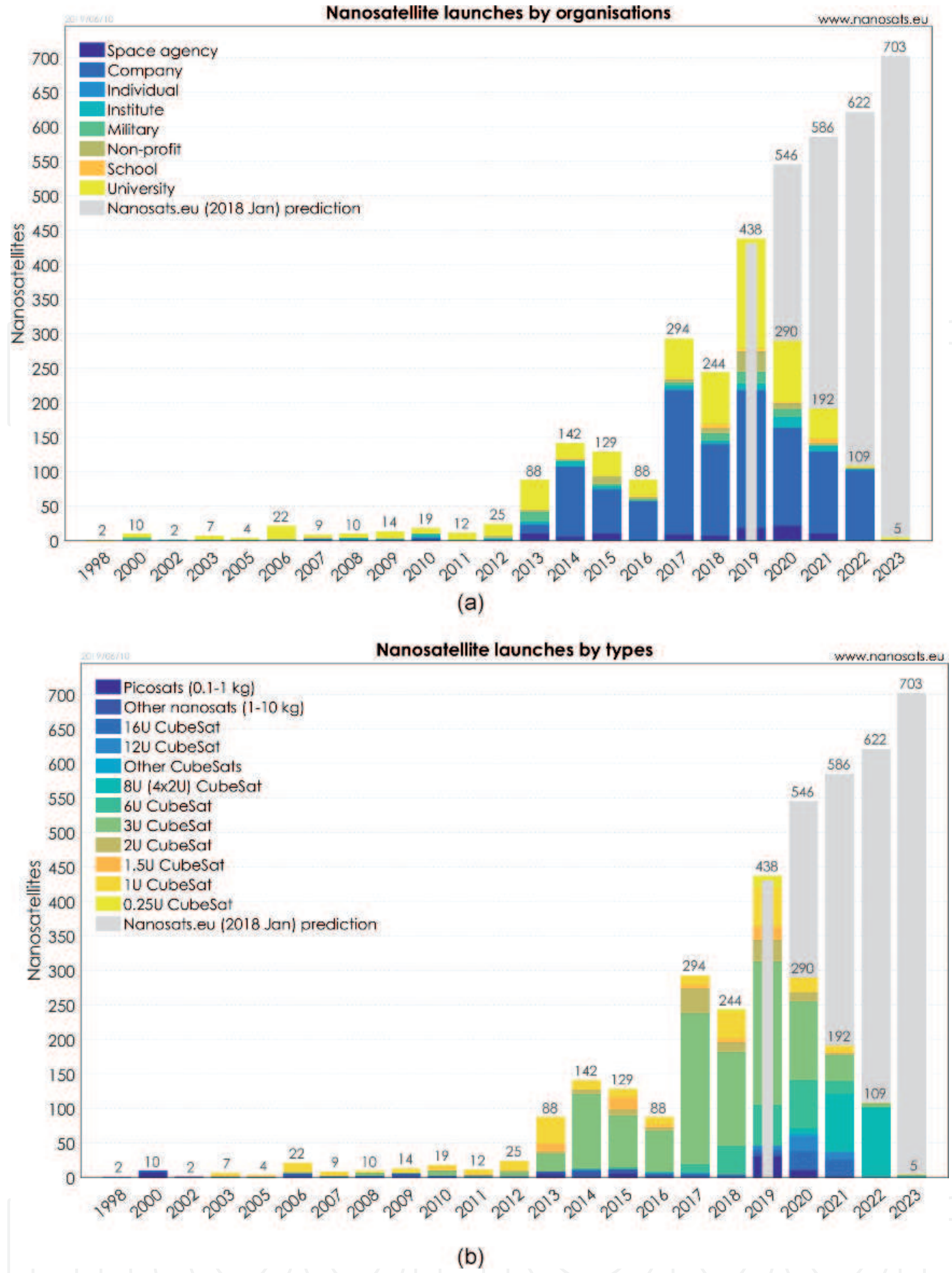


Figure 4.
The number of nanosatellites launched per year and (a) organization or (b) form factor [21].

passive microwaves applications, in dark green to EO active microwaves applications, and in light orange typically to IoT and M2M communications. In the next sections, we will focus on the EO applications but keeping in mind that future advances in satellite communication networks will also improve the performance of EO systems and enable new ones as well as distributed ones (e.g., large synthetic apertures).

The interested reader is encouraged to consult [21] for the most updated information as these numbers can change rapidly. Note that the number of CubeSats that can be launched in a single rocket can be very high. The current record is held by the Indian rocket PSLV-C37 that, on February 15, 2017, launched Cartosat-2D and 103 CubeSats, from which 88 are from the Planet Labs Inc. and 8 are from the Spire Global Inc. The interested reader is invited to see the deployment of these satellites from the onboard camera at [24].

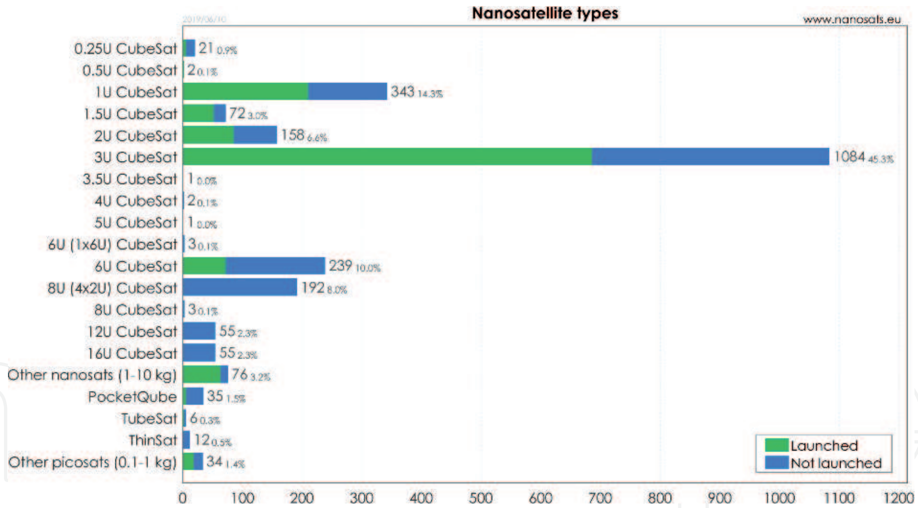


Figure 5.
The number of CubeSats by form factor [21].

Organization	Launched/ planned size	First launch	Form factor	Field	Technical and comments
Planet Labs	355/150	2013	3 U	Earth observation	29 MP sensor taking images with 3.7 m ground resolution and swath of 24.6 km × 16.4 km from 475 km altitude
Spire	103/150	2013	3 U	Weather, AIS, ADS-B, earthquake	Measure change in GPS signal after passing atmosphere to calculate precise profiles for temperature, pressure, and humidity. Investigating earthquake (ELF) detection
AprizeSat	12/12	2002	Microsat	IoT/M2M	Low-cost satellite data services for monitoring the fuel level and oil and gas pipelines and mobile tracking of shipping containers, railcars, and trailers
GeoOptics	7/N/A	2017	6 U	Weather	Using GPS radio occultation for weather data
Swarm Technologies	7/150	2018	0.25 U, 1 U	IoT/M2M	World's smallest two-way communication satellites
Commsat	7/72	2018	Microsat, 6 U, 3 U	IoT/M2M, AIS	Ladybeetle 1 is 100 kg and 3 CubeSats of 6 U and 3 of 3 U. Plans 4 more in 2019 and complete 72 satellites in 2022
Astro Digital	6/25	2014	6 U, 16 U	Earth observation	6 U has 22 m resolution in RGB and NIR. 16 U has 2.5 m resolution in RGB, red edge, and NIR with 70 MP sensor
Fleet Space	4/100	2018	3 U, 12 U, 1.5 U	IoT/M2M	Main constellation potentially with 12 U CubeSats
Sky and Space Global	3/200	2017	8 U, 6 U, 3 U	IoT/M2M	Communication service (voice, data, and M2M). Plans to use inter-satellite links

Organization	Launched/ planned size	First launch	Form factor	Field	Technical and comments
NanoAvionics	2/72	2017	6 U, 12 U	IoT/M2M	Global IoT constellation-as-a-service system aimed at IoT/M2M communication providers
Helios Wire	2/30	2017	6 U, 16 U	IoT/M2M	Uses 30 MHz of S-band spectrum to receive tiny data packages from billions of sensors
Kepler Communications	2/140	2018	3 U, 6 U	IoT/M2M, Internet	IoT/M2M data communication network. Monthly fee based on the data amount. Hope to achieve rates of 1–40 Mbps
Analytical Space	1/N/A	2018	6 U	IoT/M2M, orbital data relay, optical comms.	In-orbit relays receiving radio and downlink to ground with laser communication enabling more data downlink from satellites
Hiber	2/48	2018	6 U	IoT/M2M	Sends small packets of data (140 characters, accompanied by time stamp, identifier, and location)
Guodian Gaoke	2/38	2018	6 U	IoT/M2M	Reliable and economical satellite IoT services and industry solutions for our customers
Astrocast	2/80	2018	3 U	IoT/M2M	Targeting L-band. Inter-satellite links. NanoSpace propulsion. Further 80 satellites in orbit by 2022
AISTech	2/150	2018	2 U, 6 U	IoT/M2M, ADS-B, AIS, IR imaging	Two-way comms., thermal imaging to detect forest fires, aviation tracking (ADS-B)
ICEYE	2/18	2018	Microsat	SAR	21-launch agreement with Vector Space Systems. 10-platform agreement with York Space Systems
Harris Corp.	1/12	2018	6 U	Weather	Immediate access to 3D wind data sets from Harris-owned HyperCubes
SIRION	1/N/A	2018	CubeSat	IoT/M2M	IoT/M2M constellation. Partnered closely with Helios Wire. Sharing spectrum and satellites
Reaktor Space	1/36	2018	6 U, 2 U	Earth observation, hyperspectral	Hyperspectral constellation for smart agriculture with 100's of spectral bands and 20 m resolution
Myriota	1/50	2018	CubeSat	IoT/M2M	Run unique, patented software which provides reliable, direct-to-satellite Internet of Things (IoT) connectivity

Organization	Launched/ planned size	First launch	Form factor	Field	Technical and comments
LaserFleet	1/192	2018	CubeSat	Internet, optical comms.	Provide reliable 1 Gbps communication rates to aircraft at altitude. Higher effective data rate at a lower cost than the best-in-class Ku/Ka/V
ADASpace	1/192	2018	Microsat CubeSat	Earth observation	Establish a global, minute-level updated Earth image data network consisting of 192 satellites
Orbital Micro Systems	1/40	2019	3 U	Weather	Weather constellation utilizes microwave technology to capture temperature and moisture measurements, refreshed and delivered every 15 minutes
Lacuna Space	1/32	2019	3 U, 6 U	IoT/M2M	IoT/M2M constellation. Selected Open Cosmos to build 3 U demonstrator

Blue for constellations for optical EO, light green for passive microwave EO, dark green for active microwave EO, and orange for IoT and M2M communications.

Table 2.
The main existing and planned CubeSats and microsat commercial constellations.

2. Science opportunities

As illustrated in **Table 2**, by 2010 the maturity achieved by CubeSats and dispensers/launchers, on one side, and by some EO technologies (high-resolution multispectral imagery and GNSS-RO), on the other side, made possible that a number of companies developed applications based on commercial constellations. Today, thanks to an intense technology R&D, the situation is completely different.

The reasons for this have been threefold. On one side, due to their small size, it has been difficult to include deployable solar panels so as to increase the electrical power generated, and, on the other side, it has been difficult to include large antenna reflectors and to transmit enough RF power so as to have a satisfactory space-to-Earth link budget. The third reason was the poor pointing accuracy that now has significantly improved thanks to miniaturized star trackers and reaction wheels. So far, these reasons have kept active optical (LIDAR) and active microwave sensors (RADAR) away from CubeSats, although it has to be stated that synthetic aperture radars (SAR) have been recently boarded in microsatellite platforms successfully (ICEYE, **Table 2**).

For spaceborne EO applications, frequency bands are restricted to those in which the atmosphere exhibits a high transmissivity, that is, the microwave and millimeter-wave parts of the radio spectrum and the long-wave infrared (LWIR), near infrared (NIR), and visible (VIS) parts of the spectrum, as illustrated in **Figure 6**.

For astronomical observations, ground-based observations are also limited to Earth's atmospheric windows in the radio and optical parts of the spectrum (**Figure 6**). Therefore, to explore the remaining parts of the EM spectrum, space-based observatories are required.

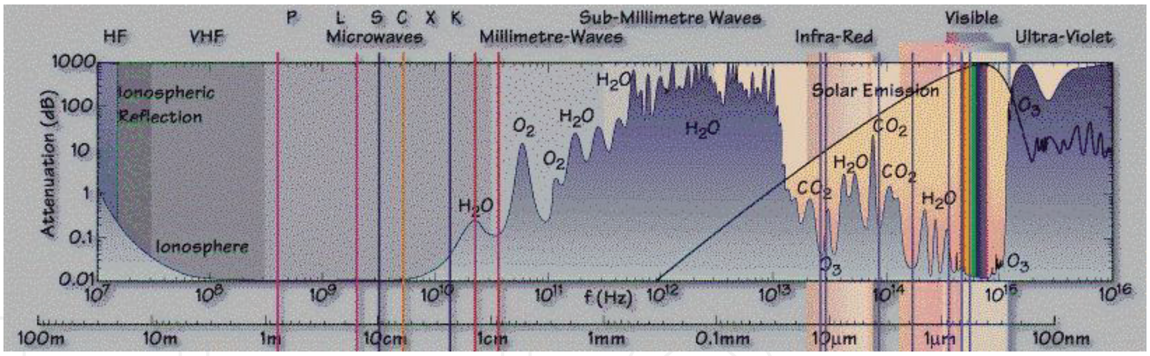


Figure 6.
Electromagnetic spectrum with different bands indicated [25].

In any case, either for EO or astronomical observations, the lower cost of individual CubeSat-based missions allows having more units, which reduces the revisit time at a given cost. This offers a number of new science opportunities [26]:

- Earth science:
  - Multipoint high temporal resolution of Earth processes
  - Mitigation of data gaps
  - Continuous monitoring
- Astrophysics:
  - Space telescopes allow access to energies across the whole electromagnetic spectrum avoiding large gaps in the radio, far IR, and the entire high-energy range (UV to γ-rays).
  - Feasibility to conduct time domain programs, which are very challenging with flagship missions such as the Hubble Space Telescope and James Webb Space Telescope.
  - Heliophysics, e.g., measurement of plasma processes in the magnetosphere-ionosphere system.
  - Planetary science: in situ investigation of planetary surfaces or atmospheres.
  - Astronomy and astrophysics: low-frequency radio science and the search for extrasolar planets.
- Biological and physical sciences, e.g., survival and adaptation of organisms to space

2.1 NASA science and technology strategy using CubeSats

Since the CubeSat standard was proposed in 1999, it took about a decade for NASA to start the Educational Launch of Nanosatellites (ELaNa) initiative in 2010. Partnerships were established with universities in the USA to design and launch CubeSats through NASA's CubeSat Launch Initiative (CSLI). Since then, 85 CubeSat missions have flown on 25 ELaNa calls, and 34 more CubeSats are manifested in 4 more calls. While it provides NASA with valuable opportunities to test emerging technologies that may be useful in future space missions, university students get involved in all phases of the mission, from the instrument and satellite design to its launch and monitoring.

As early as 2012, NASA's Science Mission Directorate (SMD) technology programs began to accommodate the use of CubeSats for validation of new science instruments and strategically promoted the use of small spacecraft to advance its science portfolio.

On one side, the Earth Science Technology Office (ESTO), which is responsible for identifying and developing technologies in support of future Earth Science Division missions, manages three major observation technology programs that solicit new awards on a 2–3-year selection cycle, as shown in **Table 3** [27].

And on the other side, following the outcomes of [28] in 2014, the Planetary Science Division (PSD) has also made significant strides toward accommodating small satellites for exploration of the solar system and for astrophysics research. **Table 4** [27] summarizes the three main planetary science technology programs.

The result of these continued investments is summarized in **Table 5**, where a number of EO techniques that were infeasible in 2012 [29] were all feasible 5 years later [30], many of them demonstrated by CubeSat missions, some of them commercial, and some even operational constellations. CubeSat-based astronomy missions will be discussed later.

Figure 7 illustrates some of these NASA CubeSat-based EO missions. They follow the 3 U or 6 U form factor and include deployable solar panels for higher electrical power generation capabilities. RainCube (**Figure 7c**) also includes a 0.5-m-diameter deployable Ka band that stows in 1.5 U. This antenna has a gain of 42.6 dBi, and it was optimized for the radar frequency of 35.75 GHz. References are provided for more information on the cited missions.

Earth science program	Approx. funding	Description
Instrument Incubator (IIP)	$28 M/year	Nurtures the development and assessment of innovative remote sensing concepts in ground, aircraft, or engineering model demonstrations (early to mid-stage development)
Advanced Components (ACT)	$5 M/year	Enables the research, development, and demonstration of component- and subsystem-level technologies to reduce the risk, cost, size, mass, and development time of missions and infrastructure
In-Space Validation of Earth Science Technologies (InVEST)	$5 M/year	Advances the readiness of existing Earth science-related technology and reduces risks to future missions through space flight validation using CubeSats

Table 3.
Earth science technology programs relevant to small satellites [27].

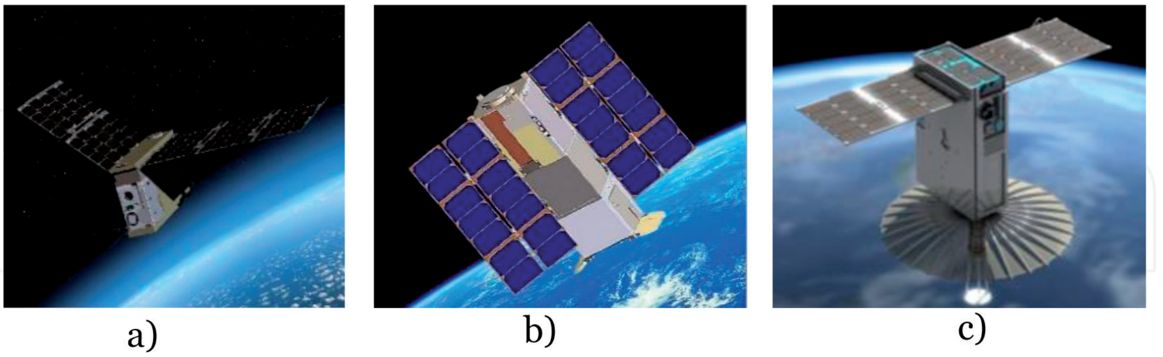
Planetary science program	Approx. funding	Description
Planetary Instrument Concepts for the Advancement of Solar System Observations (PICASSO)	$4 M/year	Supports the development of spacecraft-based instrument components and systems that show promise for future planetary missions. The program supports early-stage technologies
Maturation of Instruments for Solar System Exploration (MatISSE)	$6 M/year	Supports the advanced development of spacecraft-based instruments that may be proposed for future planetary missions that are at the middle stages of technology readiness
Development and Advancement of Lunar Instruments (DALI)	$5 M/year	Supports the development of science instruments for small lunar landers and orbital assets that are at the middle stages of technology readiness

Table 4.
Planetary science technology programs relevant to small satellites [27].

Technology	2012 technology review by Selva and Krejci	2017 technology review by Freeman et al.	Justification
Atmospheric chemistry instruments	Problematic	Feasible	PICASSO, IR sounders
Atmospheric temperature and humidity sounders	Feasible	Feasible	—
Cloud profile and rain radars	Infeasible	Feasible	JPL RainCube demo
Earth radiation budget radiometers	Feasible	Feasible	SERB, RAVAN
Gravity instruments	Feasible	Feasible	No demo mission
Hi-res optical imagers	Infeasible	Feasible	Planet Labs.
Imaging microwave radars	Infeasible	Problematic	Ka-Band 12 U design
Imaging multispectral radiometers (Vis/IR)	Problematic	Feasible	AstroDigital
Imaging multispectral radiometers (μW)	Problematic	Feasible	TEMPEST
Lidars	Infeasible	Problematic	DIAL laser occultation
Lightning imagers	Feasible	Feasible	—
Magnetic field	Feasible	Feasible	InSPIRE
Multiple direction/ polarization radiometers	Problematic	Feasible	HARP Polarimeter
Ocean color instruments	Feasible	Feasible	SeaHawk
Precision orbit	Feasible	Feasible	CanX-4 and CanX-5
Radar altimeters	Infeasible	Feasible	Bistatic LEO-GEO/ MEO
Scatterometers	Infeasible	Feasible	CYGNSS (GNSS-R)

In red: commercial companies.

Table 5.
EO technologies for CubeSat-based missions [29, 30].



a) b) c)

Figure 7.
Artist's view of (a) TEMPEST [31], (b) RAVAN [32], and (c) RainCube missions [33].

2.2 ESA science and technology strategy using CubeSats

On the educational side, the ESA launched in February 2008 the first Call for CubeSat Proposals to universities in ESA member and cooperating states. Seven student-built CubeSats were launched onboard the Vega maiden flight on February 13, 2012. Since then, 12 more CubeSats have been enrolled in the first and second editions of the "Fly Your Satellite!" program.

Since 2013, the ESA has invested more than 16 M€ as part of the General Support Technology Program (GSTP) FLY Element [34], in 12 CubeSat IOD missions [35, 36]. As part of ESA's Systems Department Project Office of the Systems

Department, Directorate of Technical and Engineering Quality, in April 2019, the CubeSat Systems Unit was created.

In addition to the work conducted by this unit, there are a number of other CubeSat-related initiatives in ESA:

- The Directorate of Telecommunications and Integrated Applications is developing a pioneer series of CubeSat missions, to test novel telecommunication technologies.

- The Directorate of Operations has OPS-SAT [37] ready to fly, an IOD test-bed for innovative mission control software.

- The Directorate of Human and Robotic Exploration is considering a CubeSat mission to test out a key capability for Mars sample return optical detection and navigation to a sample container from the orbit.

- The Science Directorate is also adapting some CubeSat technologies for operation in the deep space environment as well as studying the potential use of CubeSats in support of planetary science missions.

- The Directorate of Earth Observation will fly FSSCat [38, 39], a double 6 U CubeSat mission for tandem observation of the polar regions and for soil moisture mapping using the FMPL-3 (UPC, ES), a combined L-band microwave radiometer and GNSS-Reflectometer using a software-defined radio, and HyperScout-2 (Cosine, NL), a VNIR and TIR hyperspectral imager enhanced with artificial intelligence for cloud detection (PhiSat-1).

The first ESA CubeSat projects are listed in **Table 6**. In addition to these missions, numerous studies have focused on the applications of CubeSat missions and

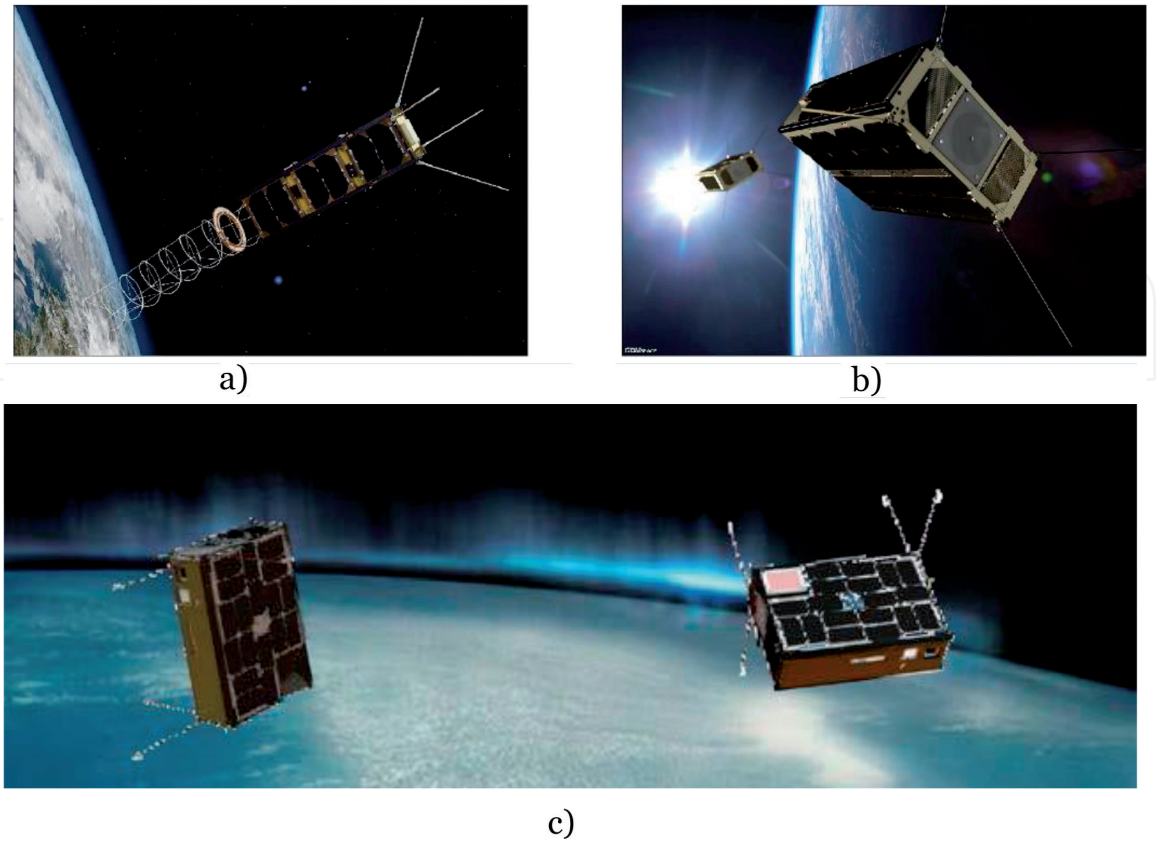


Figure 8.
Artist's view of (a) GOMX-3 [35] and (b) GOMX-4 [36] nanosatellites in space (credits GomSpace) and (c) FSSCat mission [38, 39].

miniaturized payloads, including remote sensing with cooperative nanosatellites, asteroid impact missions, lunar CubeSats, astrobiology/astrochemistry experiment CubeSats, asteroid observer missions, etc.

Organization	Mission	Launch	Form factor	Field	Technical and comments
GomSpace (DK)	GOMX-3	2015	3 U	Tech demo	ADS-B, GEO Satcom signal monitoring, X-band transmitter (**Figure 8a**)
GomSpace (DK)	GOMX-4B	2018	2 × 6 U	Tech demo Earth observation	Inter-satellite link and propulsion while in tandem with GOMX-4A (GomSpace, Ministry of Defense, DK), star tracker HyperScout compact hyperspectral VNIR imager (Cosine, NL) (**Figure 8b**)
VKI (BE)	Qarman	2019	3 U	Tech demo	Demonstrates reentry technologies, novel heatshield materials, new passive aerodynamic drag stabilization system, and telemetry transmission during reentry via data relay satellites in low Earth orbit
RMI (BE) **KU Leuven (BE)**	SIMBA	2019	3 U	Earth observation	Total solar irradiance and Earth radiation budget
BIRA-IASB (BE) **VTT (FI)** **Clyde Space (UK)**	PICASSO	2019	3 U	Atmosphere and ionosphere	Stratospheric ozone distribution, mesospheric temperature profile, and ionospheric electron density
C3S and MTA EK (HU) **ICL (UK)** **Astronika (PO)**	RadCube	2019	3 U	Tech demo Space weather	3 U platform In situ space radiation and magnetic field in LEO
RUAG (AU) **TU Graz (AU)** **Seibersdorf Labor GmbH (AU)**	PRETTY	—	3 U	Earth observation	GNSS-R at low grazing angles, radiation dosimeter
ESA	OPS-SAT	2019	3 U	Tech demo	Experimentation with onboard and ground software by offering a safe and reconfigurable environment
UPC (ES) **Golbriak (EE)** **Deimos Eng (PT)** **Tyvak Intl. (IT)** **Cosine (NL)**	FSSCat	2019	2 × 6 U	Tech demo Earth observation	RF and O-ISL, federated satellite experiment ^{3}Cat-5/A: Microwave radiometer and GNSS-R (UPC, ES) ^{3}Cat-5/B: HyperScout-2 VNIR + TIR hyperspectral imager (Cosine, NL) (**Figure 8c**)

In blue from the CubeSat Systems Unit, Directorate of Technical and Engineering Quality; in orange from the Directorate of Operations; and in green from the Directorate of Earth Observation (2017 ESA S^3 Challenge, Copernicus Masters Competition).

Table 6.
The first ESA CubeSat-based missions.

3. Astronomy and interplanetary missions using CubeSats

As highlighted in Sections 1.3 and 2.1, the majority of the CubeSats orbiting today are devoted to Earth observation, notably from two commercial companies, followed by communications. In the coming years, these two categories will still dominate. Although the largest increase will occur in communication satellites, the growth in scientific (non-EO) missions will not be negligible (from 10 to 20%, **Figure 9**) considering that the predicted number of satellites to be launched is going to multiply by more than a factor of 3 (see **Figure 4**).

In particular, until 2017 there were only 5 astronomy missions, and in the field interplanetary missions, until 2018 only 14 nano−/microsatellites had been launched to destinations outside the LEO. Beyond-the-Earth orbit is the domain of civil agencies who, for the sake of reliability, have been historically reluctant to invest in small satellites. However, things may be changing, since only in 2018 four nano−/microsatellites made their way beyond the Earth orbit, which is more than those in the previous 5 years all together, and 35 more are expected to be launched in the coming 5 years. Naturally, most of them target the moon, but a non-negligible fraction will be devoted to interplanetary missions (**Figure 10**).

As in other fields, at the beginning all the astronomy or heliophysics missions were conducted by universities, and it was not until 2017 that the first NASA JPL mission (ASTERIA) was launched. Achieving state-of-the-art astronomy with CubeSats has become possible due to advances in precision pointing, communications technology, and deployables, among others (Tables 5.1 and 5.2 of [40]). **Table 7**, distilled from [21], shows the main astronomy and beyond-the-Earth past and planned missions. It also shows that the majority of these missions are based on the 6 U form factor, which is the smallest one capable to accommodate all the advanced attitude determination and control systems (ADCS), larger deployable solar panels and antennas, as well as telescope optics. It is also remarkable that so far there are no funded CubeSat missions in the far IR because the thermal stability and detector cooling require cryo-coolers for CubeSats that have yet to be developed for astrophysics due to power and space limitations [41].

It is worth noting that the large number of CubeSats to be launched to the Moon in 2020 corresponds to the Artemis-1 mission (**Figure 11**), formerly known as Exploration Mission-1. The first mission for NASA's Orion rocket and the European Service Module will send the spacecraft beyond the moon and back. Thirteen low-cost CubeSat missions were competitively selected as secondary payloads on the Artemis-1 test flight, all of them having the 6 U form factor. The selected CubeSats are Lunar Flashlight, Lunar South Pole, Near-Earth Asteroid Scout,

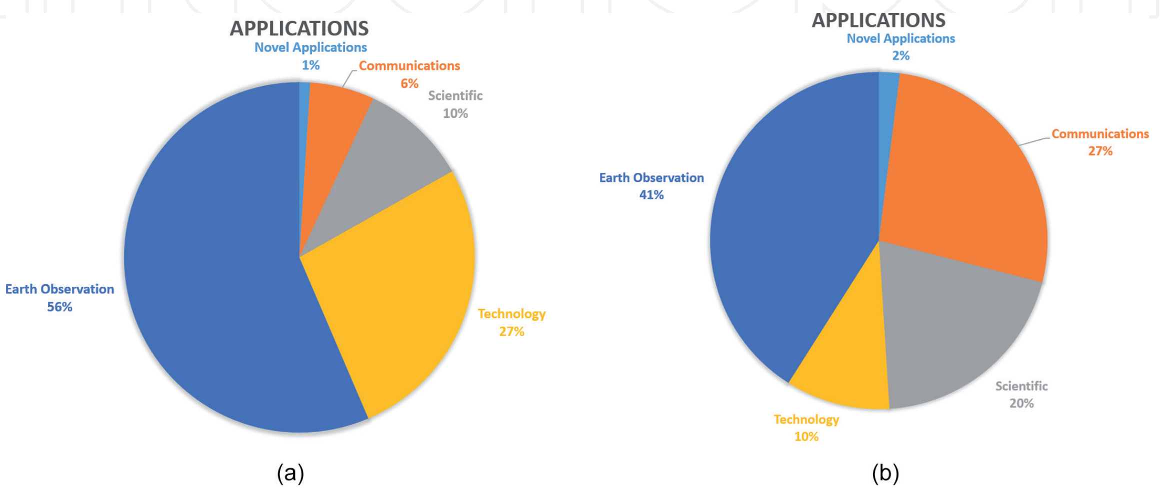


Figure 9.
Satellite application trends (1–50 kg): (a) 2014–2018 and (b) 2019–2023 (adapted from [14]).

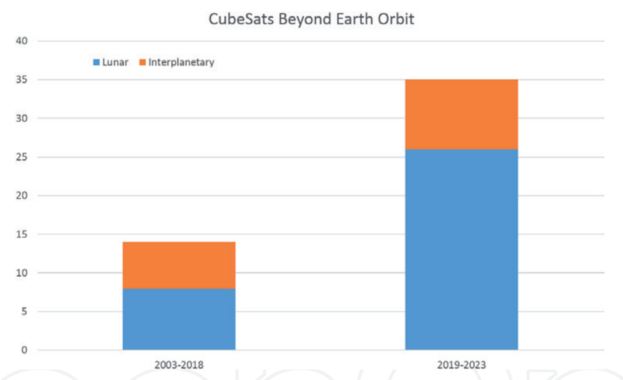


Figure 10.
CubeSats launched beyond the earth orbit: 14 from 2003 to 2018 and 35 planed from 2019 to 2023 (adapted from [14]).

Organization	Mission	Launch	Form factor	Technical and comments
Morehead State University Kentucky Space	CXBN	2012	2 U	• Cosmic X-ray background (CXRB) in the 30–50 keV range
University of Colorado	CSSWE	2012	3 U	• Measures the directional differential flux of solar energetic protons (SEPs) and Earth's radiation belt electrons
Austria Canada Poland	BRITE	2013 2014	8 U (2 × 2 × 2)	• BRITE Target Explorer Constellation: BRITE-Toronto, BRITE-Heweliusz, UniBRITE, BRITE-Austria, BRITE-Lem, BRITE-Montreal • Conducts photometric observations of some of the brightest stars in the sky to examine their variability. Observations will have a precision at least 10x better than achievable from ground-based observations
University of Colorado at Boulder	MinXSS	2015	3 U	• Provides spectral observations of the solar X-rays near the maximum of solar cycle 24 from 0.6 keV (20 Å) to 25 keV (0.5 Å)
JPL (USA) MIT (USA)	ASTERIA	2017	6 U	• Detects exoplanetary transits across bright stars • Pointing accuracy of ±0.003° (1σ) for 2 axes and ± 0.007° (1σ) for the third axis, with 0.5″ rms over 20 min, pointing repeatability of 0.001″ rms from orbit to orbit • ±0.01 K level temperature stability of the imaging detector
ERC, CNRS, ESEP Lab, PSL Université Paris, Fondation MERAC, CNES, CCERES and Obs. de Paris – LESIA	PicSat	2018	3 U	• To observe in visible light the potential transit of the • directly imaged giant planet β Pictoris b and perhaps even its moons and debris

Organization	Mission	Launch	Form factor	Technical and comments
University of Iowa	HaloSat	2018	6 U	• Measurement of soft X-ray emission from the hot halo of the Milky Way galaxy to resolve the missing baryon problem. Measure O VII and O VIII line emission in 400 fields (FOV ~ 10°) over 90% of the sky. Study of solar wind charge exchange emission to remove uncertainty on the oxygen line emission measurements • First NASA-funded astronomy mission
Spacety (China)	Tongchuan-1	2018	6 U	• Detects signals from gamma-ray bursts, to identify and locate the electromagnetic counterparts to gravitational waves
University of Colorado Boulder	MinXSS-2	2018	3 U	• As MinXSS
University of Colorado	CSIM	2018	6 U	• Observes the solar spectral irradiance
DARPA	SHFT-1	2018	3 U	• Collects radio-frequency signals in the HF (5–30 MHz) band to study the galactic background emissions, the HF signals from Jupiter, and the signals from terrestrial transmitters after having passed through the Earth's ionosphere
NASA	MarCO-1/ MarCO-2	2018	6 U	• Data relay to send data back to Earth during InSight's entry, descent and landing operations at Mars. Technology capability demonstration of communications relay system
University of Hawaii at Manoa	NEUTRON-1	2019*	3 U	• Measures low-energy neutron flux in LEO environment
Boston University	CuPID	2019*	6 U	• Miniaturized soft X-ray imaging telescope
University of Colorado Boulder	CUTE	2020	6 U	• To conduct a survey of exoplanet transit spectroscopy in the near UV of a dozen short-period, large planets orbiting F,G, and K stars to constrain stellar variability and measure mass loss rates • Second NASA-funded astronomy mission
Isaware (FI)	XFM Cube	2020	3 U	• Measuring X-ray fluxes
Lockheed Martin	LunIR	2020	6 U	• Lunar flyby to collect spectroscopy and thermography (MWIR sensor) for surface characterization, remote sensing, and site selection
Arizona State University	LunaH-Map	2020	6 U	• High-resolution mapping of hydrogen content of the entire south pole of the moon, including permanently shadowed regions up to a meter beneath the lunar surface

Organization	Mission	Launch	Form factor	Technical and comments
NASA JPL	Lunar Flashlight	2020	6 U	• Illuminates with lasers in four different bands the permanently shadowed regions and detect water ice absorption bands in the near-infrared
Morehead State University	Lunar IceCube	2020	6 U	• Prospects for water ice and other lunar volatiles as a function of time of day, latitude, and regolith composition/mineralogy from a low-perigee lunar orbit flying only 100 km (62 miles) above the lunar surface
Arizona State University (USA)	SPARCS	2021	6 U	• Monitoring in the far (153–171 nm) and near UV (258–308 nm) of low-mass stars (0.2–0.6 MΘ); the most dominant hosts of exoplanets • Each star observed for at least one stellar rotation (4–45 days) • Third NASA-funded astronomy mission
NASA's Goddard Space Flight Center	BurstCube	2021	6 U	• Detection of gamma ray transients in the 10–1000 keV energy range. Valuable capability to catch the predicted counterparts of gravitational wave sources • Fourth NASA-funded astronomy mission
ESA **Luxembourg Space Agency (LU)** **GomSpace (DK)**	M-ARGO	2023	12 U	• Demonstrating asteroid rendezvous and identifying in situ resources with multispectral imager and laser altimeter
ESA	HERA CUBESAT	N/A	2x6 U	• Observing asteroid and deflection assessment

Table 7.
Non-comprehensive list of astronomy and beyond-the-earth CubeSat-based missions.

BioSentinel (carrying the first living creatures into deep space since 1972), SkyFire, Lunar IceCube, CubeSat for Solar Particles (CuSP), Lunar Polar Hydrogen Mapper (LunaH-Map), EQUULEUS, OMOTENASHI, ArgoMoon, Cislunar Explorers, Earth Escape Explorer (CU-E^3), and Team Miles.

Talking about interplanetary missions, on May 5, 2018, NASA launched a stationary lander called InSight to Mars. InSight landed on Mars on November 26, 2018. Riding along with InSight were two CubeSats—the first of this kind of spacecraft ever to fly to deep space [42]. Both MarCO-A and MarCO-B succeeded in a flyby of Mars, relaying data to Earth from InSight as it landed on Mars. **Figure 12** shows an artist view of the MarCOs with the reflectarray used for communication purposes.

In addition to the "classical" astronomy, lunar and Martian missions cited above, CubeSats are nowadays finding their way to other bodies of the solar system, and there are proposals [43] to send them to Venus (CUVE mission), Deimos and Phobos asteroids (PRISM and PROME missions), comets (PrOVE mission), or Jupiter (ExCSITE mission, [44]). **Figure 13** from [44] illustrates the LEO and beyond-LEO CubeSat exploration initiatives.

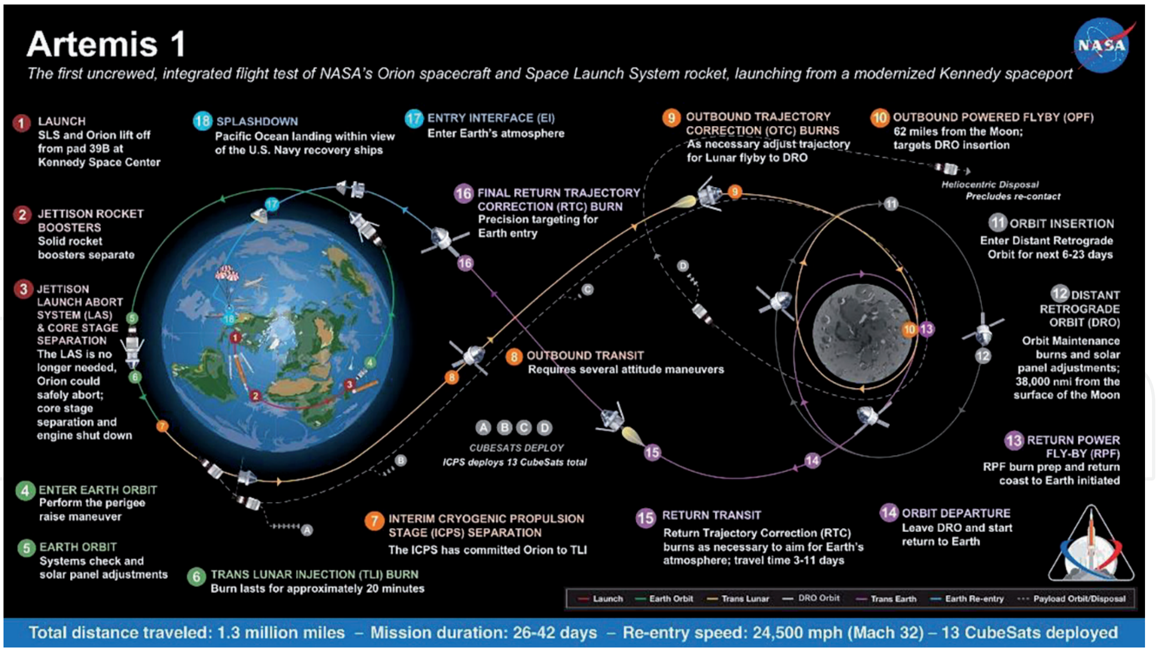


Figure 11.
Overview of the mission plan for Artemis-1: CubeSats will be deployed at steps A, B, C, and D [https://www.nasa.gov/image-feature/artemis-1-map].

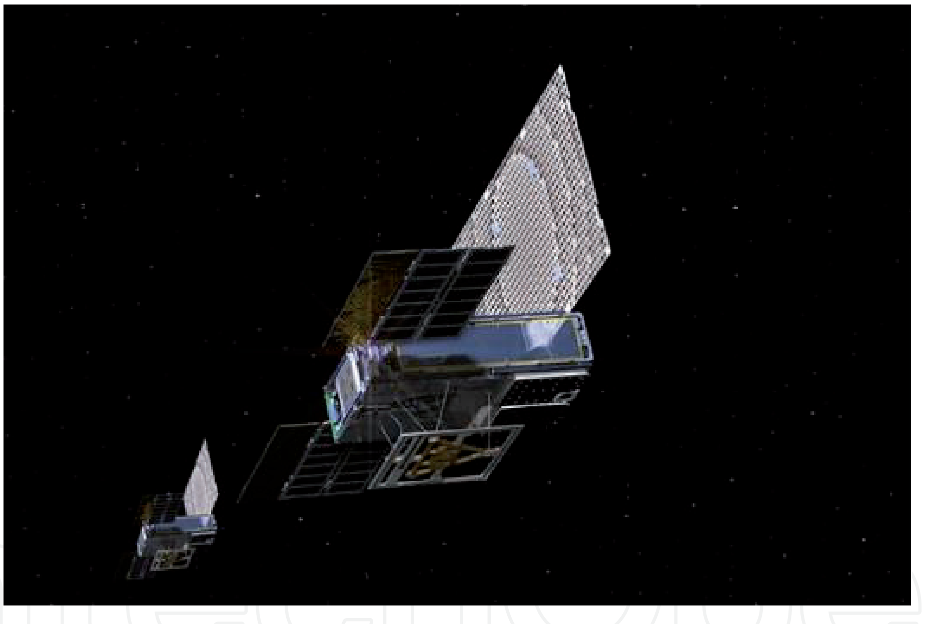


Figure 12.
Artist view of MarCO-A and MarCO-B [42].

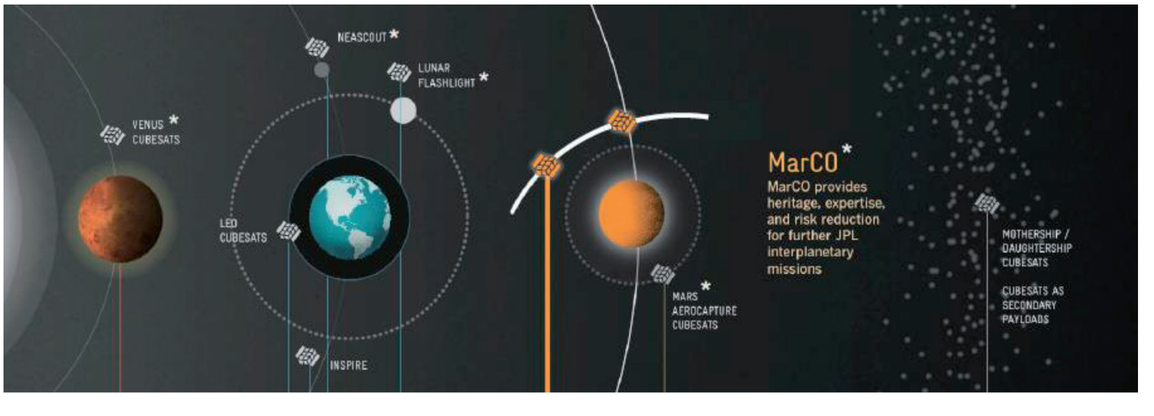


Figure 13.
Solar system exploration with CubeSats and nanosats [44].

4. Conclusions and way forward

Since its conception in 1999, CubeSats have produced a "disruptive innovation": from simple applications at the bottom of a market (mostly educational), they have relentlessly moved up, eventually displacing established medium-size competing satellites. However, CubeSats cannot displace all the large space missions as physics laws cannot be changed, i.e., large apertures and focal lengths are required to collect faint signals and achieve large angular resolution. However, CubeSats are finding their own niche in many Earth observation, astronomical, and communications applications where short revisit times or even continuous monitoring is required.

Early CubeSats typically had short lifetimes once in orbit (a few months), but with increased ground testing and added redundancies, lifetimes have grown significantly, up to 4–5 years in some cases.

Despite all these outstanding improvements, in order to exploit the full potential of CubeSats, many technologies still need to be developed. **Table 8** summarizes the enabling technologies required for different science applications, indicating in red the most challenging technologies and applications, notably increased communications performance, reliability, thermal stability, and calibration accuracy, to form constellations or formation flying satellite topologies to create large interferometers and distributed apertures.

Science discipline	Enabling technology	Example application
Solar and space physics	Propulsion	Constellation deployment and maintenance, formation flying
	Sub-arcsecond attitude control	High-resolution solar imaging
	Communications	Missions beyond low Earth orbit
	Miniature field and plasma sensors	In situ measurements of upper atmosphere plasmas
Earth science	Propulsion	Constellations for high-temporal resolution observations and orbit maintenance
	Miniaturized sensors	Stable, repeatable, and calibrated datasets
	Communications	High data rates
Planetary science	Propulsion	Orbit insertion
	Comms&Comms Infrastructure	Direct/indirect to Earth communications
	Radiation-tolerant electronics	Enhanced reliability in planetary magnetospheres, long flights
	Deployables	Deployable solar panel enhanced power generation
		Deployable mirrors and antennas
Astronomy and astrophysics	Propulsion	Constellations for interferometry, distributed apertures
	Sub-arcsecond attitude control	High-resolution imaging
	Communications	High data rate
	Deployables	Increased aperture and thermal control
	Miniaturized sensors	UV and X-ray imaging
Physical and biological	Thermal control	Stable payload environment

Table 8.
CubeSat-enabling technologies and potential applications for each science discipline (adapted from [40]).

In the field of Earth observation, future developments in nanosat sensors will likely occur:

- In the field of passive microwave sensors:
    - Miniature microwave and millimeter-wave radiometers for weather applications, such as the MiniRad which is onboard the Global Environmental Monitoring System (GEMS) constellation from Orbital Micro Systems [45], or
    - GNSS-R instruments with real-time processing for target detection/identification [46] or—as larger downlink bandwidths are available—with raw data acquisition and on-ground processing to optimize the processing according to the target, as planned in FMPL-3, the evolution of the FMPL-2 on board FSSCat [38, 39].
- In the field of passive VNIR/TIR hyperspectral imagers, imagers will include a larger number of bands but will include advanced image compression algorithms to minimize the amount of information to be downloaded and will incorporate artificial intelligence to download only the information extracted instead of the raw data.

Also, both their calibration will have to be refined so as to improve the quality of the scientific data.

Due to power and antenna size requirements, active microwave sensors (e.g., radar altimeters and SARs) will likely remain in domain of mini- and microsats (< 100 kg, e.g., ICEYE constellation [47]), and it is unlikely that active optical sensor technology (i.e., lidars) develops in small satellites in the midterm.

In the field of astronomy, and in particular heliophysics, NASA has also been taking the lead. In 2017 NASA selected nine proposals under its Heliophysics Small Explorers Program [48]: (1) the Mechanisms of Energetic Mass Ejection Explorer (MEME-X), (2) the Focusing Optics X-ray Solar Imager (FOXSI), (3) the Multi-Slit Solar Explorer (MUSE), (4) the Tandem Reconnection and Cusp Electrodynamics Reconnaissance Satellites (TRACERS), (5) the Polarimeter to Unify the Corona and Heliosphere (PUNCH), (6) the Atmospheric Waves Experiment (AWE), (7) the US Contributions to the THOR mission (THOR-US), (8) the Coronal Spectrographic Imager in the Extreme ultraviolet (COSIE), and (9) the Sun Radio Interferometer Space Experiment (SunRISE) mission concept, which is a space-based sparse array, composed of formation flying of six SmallSats designed to localize the radio emission associated with coronal mass ejections (CMEs) from the sun [49].

More recently, in August 2019, NASA selected two proposals to demonstrate SmallSat technologies to study interplanetary space [50]: (1) Science-Enabling Technologies for Heliophysics (SETH) will demonstrate two technologies, an optical communications technology and experiment to detect solar energetic neutral atoms as well as an array of waves and other particles that erupt from our sun, and (2) Solar Cruiser, which will deploy a nearly 18,000 square foot solar sail and a coronagraph instrument that would enable simultaneous measurements of the sun's magnetic field structure and velocity of coronal mass ejections or CMEs.

As a final thought, quoting Prof. Puig-Suari, "Before cubesats, we were so conservative nobody was willing to try anything out of the ordinary. When we did, we discovered some of the things everybody said would not work, did work. The fundamental change was that there was a mechanism to go try to those things. Some will work and some will not, but it allows us to try them and that was very infrequent before cubesats arrived. That was really important. That was the big change." And this is just the beginning of a new way to do Earth observation, astronomy, and satellite communications much more, in a different and more efficient way than it was done in the past decades. What will the future bring? Nobody knows, but certainly the future is being shaped today with these novel technologies, and only our imagination will set the limits.

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